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SPUTTERING OF A VEHICLE'S SURFACE IN A SPACE ENVIRONMENT

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SUMMARY

A brief survey of current investigations of physical sputtering is given, from which estimates are made of the sputtering yields by constituents found in a vehicle's environment. The rates at which a vehicle's surface is sputtered by the earth's atmosphere, by radiation belts, and by solar corpuscular radiation are calculated. It is shown that the atmospheric sputtering constitutes a serious problem at low orbital altitudes and that the damage at 1 A. U. by solar corpuscular radiation is within an order of magnitude of that caused by micrometeorites.

Recommendations are made regarding areas of investigation which are needed.

INTRODUCTION

Sputtering is the removal of atoms and molecules from a surface bombarded by high velocity impinging particles. It is uncertain whether serious damage to the skin of a spacecraft will result from the craft's exposure to a space environment. This report provides an estimate of the extent of such damage.

Due to the meager knowledge of sputtering yield (number of particles removed per impinging particle) under high vacuum conditions for particles and energies found in space, it is necessary to survey the present state of the art and to make estimates of the applicable yields.

Since little is known of the differential energy spectrum of the fluxes over the entire energy spectrum to which the vehicle is subjected, the tentative sputtering rates determined here are good to only within an order of magnitude. A portion of the material found in this note was contributed by Convair from their collection of literature on sputtering.

STATE OF THE ART SURVEY

Sputtering of cathodes in glow tubes and vacuum tubes has been observed since the middle of the nineteenth century. Experimental work has been carried on since around 1925, but has been hampered until recently by the poor vacuums attained, lack of precision measuring equipment, and a general lack of interest in investigation of the sputtering parameters (such as energy dependence, angular dependence, and dependence on impinging atom-target atom interaction).

Two theories of sputtering were introduced about 1930, the "hot-spot"-evaporative theory and the momentum transfer theory. The evaporative theory assumes that the impacting particle transfers energy to the local surface and raises the temperature of a small hemispherical region of atomic dimensions high enough to evaporate the enclosed material. The angular distribution of the sputtered material should follow a cosine distribution. The sputtering yield should depend only on the energy of the incoming particle and not on its nature, according to the evaporative theory. Also, the sputtered particles should have velocities corresponding to the thermal evaporation energies. Recent experiments conducted under well-controlled conditions have shown that none of these predictions are correct [1, 2, 3].

The momentum-transfer theory is today quite well accepted as the means of ejection for all energies. This theory assumes that the impinging particle transfers sufficient momentum to a surface-bound particle for the impacted particle to escape from the surface. (The impinging particle will hereafter be called the "ion" according to accepted convention, without necessarily implying that the particle is not electrically neutral.) Neither the mechanism of transfer nor the energy which the bound particle must have is known. The energy required is thought to be either the energy of sublimation ($\sim$4ev, depending on the material and on the location of the atom in the crystal structure) or the displacement energy in radiation damage theory ($\sim$25 ev for most substances). Several mechanisms which have been proposed to transfer momentum from the ion to the sputtered particle are:

(1) Direct "billiard ball" collisions between the ion and atoms in which either: the ion eventually strikes the lower side of an atom directly or by rebound, transferring sufficient energy to overcome the binding force [4], or the force is transmitted by hard collisions in the direction of close-packed chains to the surface or to a dislocation [5].

(2) An atom displaced by a hard collision with the ion acts with the crystal lattice potential on a nearby atom, displacing the second atom beyond the binding range of the lattice potential of other surface atoms [6].

(3) An analysis along the lines of neutron diffusion theory, considering the number of displacements produced by the ion to be predictable by means used in radiation damage theory [7].

(4) A mechanism for which the analysis can be accomplished by straightforward application of neutron diffusion theory. The parameters involved have not been evaluated [8].

(5) A diffusion mechanism valid only for high energies, using a constant rate of displacement over the range in which sputtering may occur, which is short compared to that of the ion's penetration [9].

The experimental data collected are subject to such varied interpretation, and the proposed mechanisms usually contain so many adjustable parameters, the values of which are not known independently, that all of the mechanisms can be substantiated by some existing data. None, however, can explain all observed facts. The correct mechanism will have the following properties.

The sputtering yield varies greatly with energy, the minimum being less than 10^{-3} at a few tens of evs and the maximum being about 10 at about 10 kev [10, 11]. Either the scattering cross section or the depth at which displacements result in sputtering must change drastically with energy and decrease beyond a specific range of energy.

Preferential sputtering takes place in the direction of close-packed chains in single crystals [12]. The sputtering yield will depend upon lattice parameters.

The sputtering yield is a function of the angle of incidence of the ions. The variation of yield with angle is not consistent between ion-target combinations, although minimum yield is always observed at normal incidence [13]. The mechanism should explain this difference in behavior as well as the functional dependence. The yield also depends on the ion-target combination [11].

The possibility exists that one mechanism is responsible for low energy sputtering and another for high energy sputtering. If this is so, they must merge into the same effect at some energy, for no consistent discontinuities in yield have been observed for various ion-target combinations.

The validity of published data is often hard to evaluate. Wehner, an accepted authority in low energy sputtering, for example, has continued to lower his thresholds and change drastically his sputtering yields with increasing refinements in his apparatus (Ref. 1 in [10]).

The published data are quite often conflicting. Illustrative of the problem are the data of Pleshivtsev [14] and Yonts, et al., [11] for sputtering of copper by H^+ at 30 kev. Pleshivtsev reports a yield, S , of 0.37 $\pm$ 30%, while Yonts reports S = 0.011 $\pm$ 20% . In analyzing the experimental procedure, the following comparisons are found.

	PLESHIVTSEV	YONTS, ET AL.
Source:	Commercial H_2 accelerated by ion gun. Output of similar gun under similar conditions mass-analyzed to be $H_1^+ \sim 40\%$ $H_2^+ \sim 50\%$ $H_3^+ \sim 10\%$ N_2^+, $O_2^+ \sim 3\%$ Energy spread not known	Commercially pure H_2 accelerated by first stage of a Calutron (es lens system) and mass-analyzed by second stage of a Calutron (180° focusing magnet) to select H_1^+. Energy spread $< \pm$ 100 ev
Target:	Copper	Oxygen-free copper
Current:	27.7 ma-hrs at 8.6 ma, measured by calorimetric means	1000 ma-hrs at 17.5 ma measured by calorimetric means, verified by electrical means
Pressure:	1 to 5 x 10^{-5} mm Hg	2 to 4 x 10^{-5} mm Hg
Method of Measuring Amount Sputtered:	24.5 mg weighed by analytic balance adjusted for weight of imbedded ions. Cleaning procedures not mentioned.	Weighed by analytic balance with target cleaned before and after sputtering, adjusted for current.
Presence of Films of Other Materials with Different Sputtering Yield:	Conditions (current and temperature) are such that surface films are probably not present, according to authors.	Authors could not determine if film was present (if so, the film was of minimum thickness.

The yield should be independent of current between about 5 and 50 ma, or more, in this pressure range. Also, pressures in this range should not affect the yield significantly. If Pleshivtsev's target were not cleaned before insertion into the apparatus, contaminations on the surface would change the sputtering yield at first; however, over 7000 Å of material was removed. Since the depth of surface contamination is much less than this, it could not account for the large discrepancy in yield. (Any change from being cleaned would lie within the 30% range of error.) In this range of pressures, the presence or absence of a film (of adsorbed materials) would change the sputtering yield only about 10%. Apparently, the reason for this variance in yield is the different sources.

Yonts' source was H_1^+. Pleshivtsev's source was not known but was assumed to be identical to that produced by a similar gun run under similar conditions; it contains H_2^+ and H_3^+ in addition to H_1^+. These should be expected to have different yields. It is generally agreed that the energy transfer factor, $4M_1M_2/(M_1+M_2)^2$, (where M_1 and M_2 are masses of particles involved in a hard elastic collision) plays a direct role in sputtering yields. (See, for example, Fig. 1, where $S(H_3^+ \rightarrow Ag) \approx 3/2\ S(H_2^+ \rightarrow Ag) \approx 3S(H_1^+ \rightarrow Ag)$ and $S(D^+ \rightarrow Ag) \approx S(H_2^+ \rightarrow Ag)$.) Assuming that $S(H_3^+ \rightarrow Cu) - 1.5\ S(H_2^+ \rightarrow Cu) = 3\,S(H_1^+ \rightarrow Cu)$, Yonts' data for the percentage constituents given for Pleshivtsev's source would be $S(40\%H_1^+,\ 50\%H_2^+,\ 10\%H_3^+ \rightarrow Cu) \simeq 0.019$.

Pleshivtsev ignored the presence of N_2^+ and O_2^+ in the beam. At 30 kev, Yonts gives $S(N_2^+ \rightarrow Cu) = 5,28$, compatible with the yields by other experimenters [15]. Using the energy transfer factor, $S(O_2^+ \rightarrow Cu) = 5.54$. If one assumes the 3% contamination as

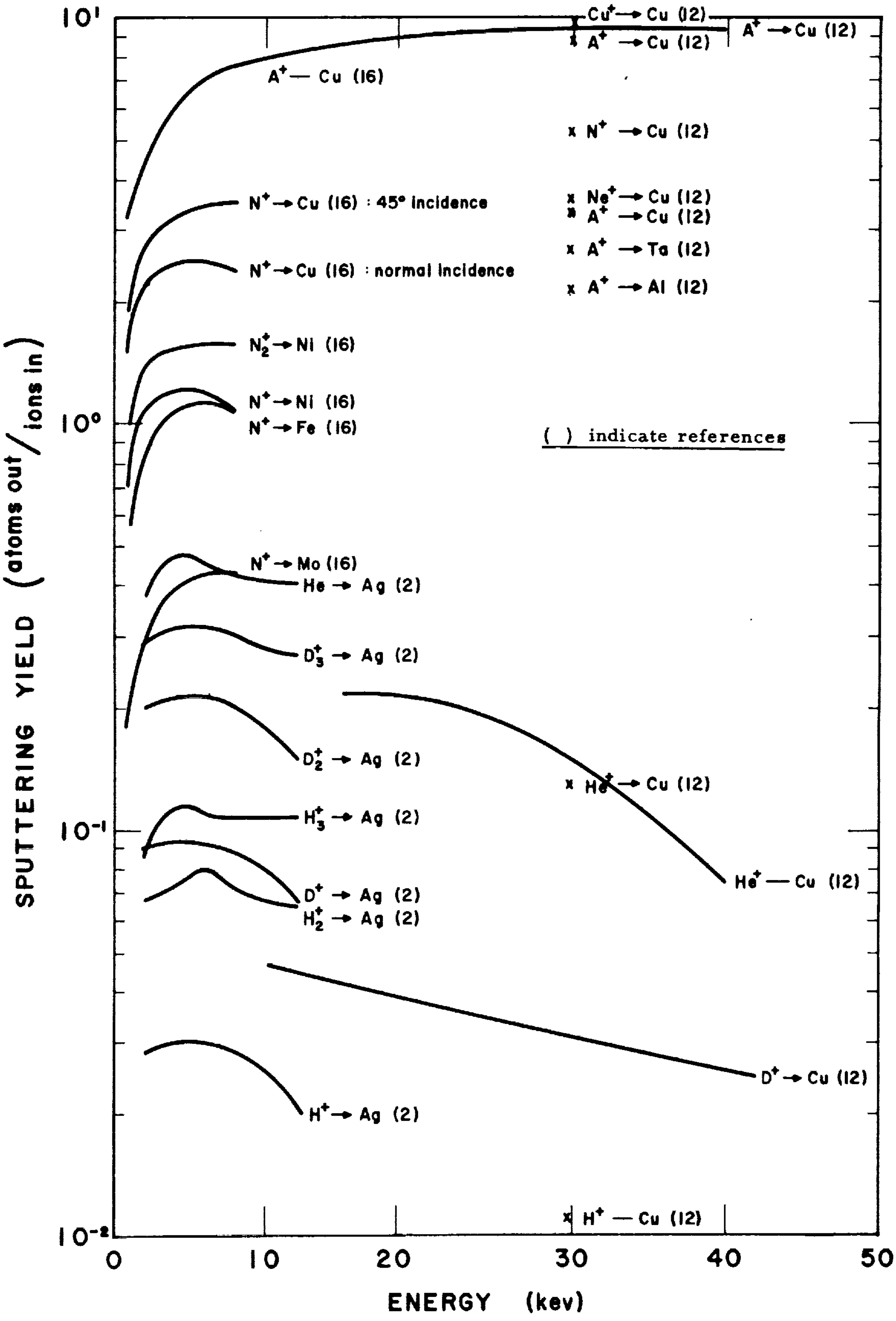

FIGURE 1. SPUTTERING YIELDS IN THE KEV ENERGY RANGE

equally N_2^+ and O_2^+, one obtains a mean sputtering yield of 5.4 for the N_2^+ and O_2^+. If one assumes a 3% contamination, 10.7 mg of material is removed by the contaminants, changing Pleshivtsev's yield to $S(H^+ \rightarrow Cu) = 0.21$. Even with these adjustments, the yields still differ by an order of magnitude and cannot be reconciled.

Two possibilities exist. If Pleshivtsev's gun has 6.5% N_2^+ and O_2^+, the hydrogen yields can be shown to be the same within the limits of error. The other possibility is that Pleshivtsev's gun contained a significant number of neutral particles; if neutral hydrogen has a much higher yield than ionized hydrogen, as suggested by Weiss, Heldt, and Moore [16][1], this might reconcile the figures for the yield of ionized hydrogen.

The two yields cannot be made compatible and since Pleshivtsev's results, by virtue of his unanalyzed beam, are more open to criticism, Yonts' results will be favored in the ensuing discussion. This decision is supported by the consistency of Yonts, et al.'s $S(H_1^+ \rightarrow Cu)$ with their other results and by harmony with the results published by others [2, 17]. Pleshivtsev has published no other data.

Similar critical analysis must be made of all the literature. The reader is often left only with the choice of accepting or rejecting the data.

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[1] The assumptions made in obtaining the estimated yield, $S(H^\bullet \rightarrow Ag)$ at 10 kev$\simeq$1.9, are believed to be incorrect. The idea that $S(H^\bullet) > S(H^+)$ may well be valid.

With the advent of continually better vacuums and ion currents precisely controlled as to energy and density, further experimentation will define clearly the effects of pressure, temperature, and beam density on measured yields. Significant contamination of the target will depend on the ratio of background pressure to operating pressure. At pressures on the order of 10^{-6} mm to 10^{-3} mm, contamination by adsorption and filming will probably be significant and tend to lower the yield. (Yields at 10^{-5} mm are on the order of 10% lower than those at 10^{-6} mm). At pressures of 10^{-3} and 10^{-2} mm, mean free paths become shorter than apparatus dimensions and sputtered atoms are returned to the surface, lowering the yield.

High temperatures of the target increase the rate of sublimation, which cannot be differentiated from sputtering, although the temperatures do reduce or eliminate adsorption. Local heating of the target by high ion densities can reduce adsorption and filming also, and do not demand as high vacuums as lower densities. Used in a good vacuum system, high densities reduce effects of background contamination. However, they do cause problems of melting and of sublimation, as well as returning some of the sputtered atoms to the surface.

The low sputtering yields (on the order of 10^{-3} or 10^{-4}) found at low energies have led to indirect methods of measuring yield, such as measuring density of radioactive tracers in a target or on a collector or observing the intensity of excitation spectra of sputtered atoms [10, 19]. These methods appear promising for collecting data from low yields in relatively short periods; investigation of their reliability, however, will have to be made before the accuracy of the results can be determined.

The sputtering yield is known to vary with the angle of incidence When an ion beam impinges on a target, the target shows an assortment of half-tear-drop-shaped holes; these cavities are thought to start at cleavage planes or grain boundaries. Photographs in [12] show a similar effect due to preferred sputtering in the direction of close-packed chains. Unless the cavities are removed (by polishing) when they are deep enough to change the macroscopic angle of incidence of the beam, the yield values obtained as a function of the angle of incidence are not valid. Apparently, this has not always been done.

Until recently, sputtering thresholds were thought to be on the order of 100 ev. As lower yields have become detectable, the threshold energies have been reduced until they are slightly above the range of energies at which displacement thresholds appear in radiation damage theory, and in some cases are slightly below. They are somewhat above the energy of sublimation divided by the energy transfer factor, but it is difficult at this time to predict to which they will finally converge (if either). Since some are below the radiation damage threshold, although they may be revised upward, we shall tentatively assume the threshold to be $E_{sublim} = 4M_1M_2/(M_1 + M_2)^2 E_t$.

Yield was previously thought to be a linear function of energy above threshold to a few hundred electron volts. The low energy curves in Fig. 2, the data for which was collected under good operating conditions and analyzed carefully, show a knee in the yield curve at about 100 ev. Stuart and Wehner's results [10] are somewhat

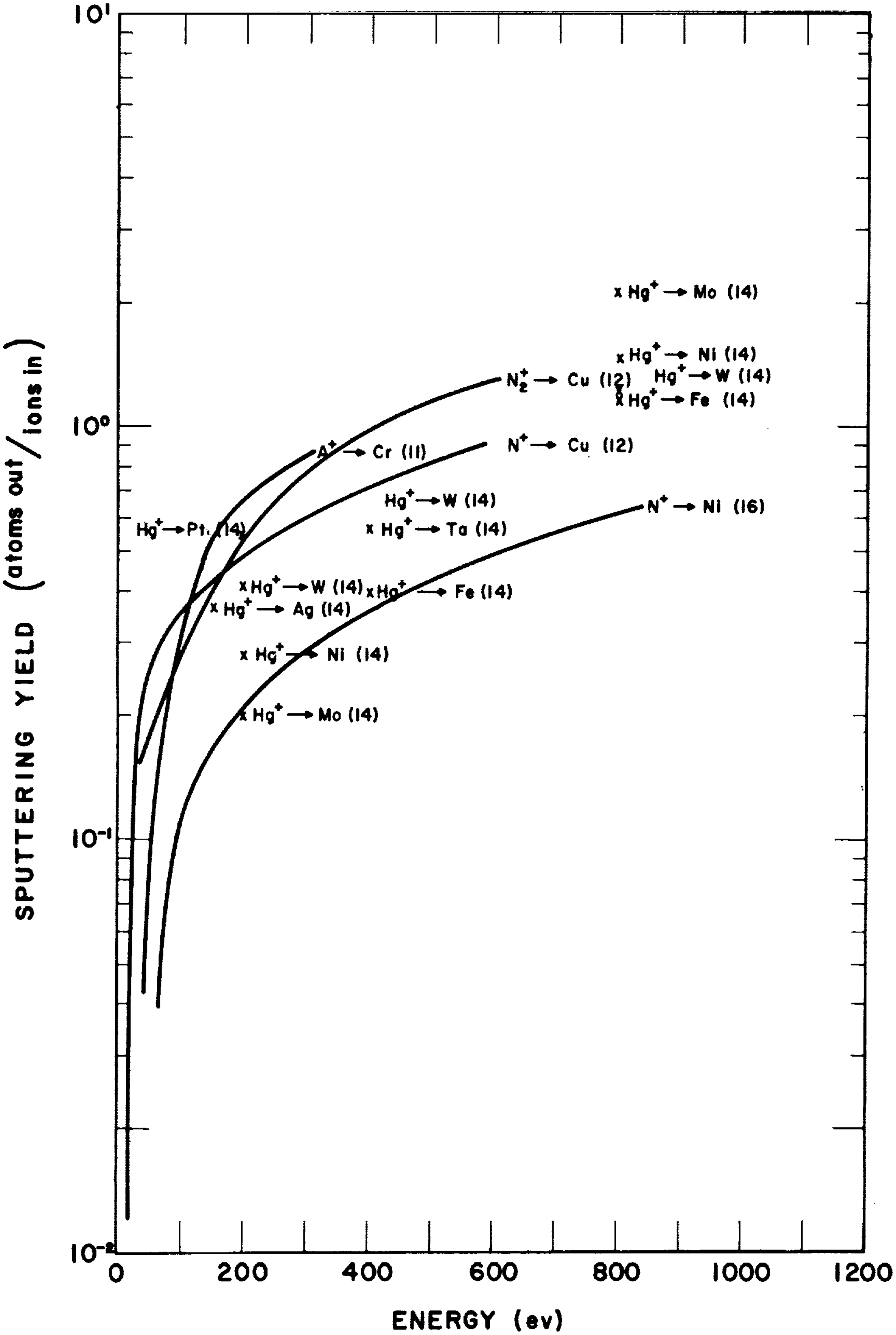

FIGURE 2. LOW ENERGY SPUTTERING YIELDS

doubtful due to their method of measuring, but they also show the knee. It is clear that the yield curve cannot be approximated by one straight line between threshold and several hundred electron volts.

Additional work with recently developed experimental techniques is needed in the kev energy range to determine the response of different targets to different ions. This range marks the maximum yield predicted by Keywell [8] and shown by data published to date. The most fruitful work on the nature of the ion-target interaction, dependence of sputtering yield on angle of incidence, etc., can be done at this level where the interactions producing sputtering have the highest cross section.

Investigations of yields should be carried on in the upper region of the energy spectrum, where the results mentioned by Pleshivtsev are the only known figures. Sputtering yields, particularly those of H and He, have to be determined in this range if accurate figures on sputtering of a vehicle are to be obtained. If sputtering is a form of radiation damage, or has a similar mechanism, sputtering by electrons should start around 200 kev. The yield of sputtering by electrons has not been determined. Judging by all known factors, it should be small, but may still prove significant if large fluxes are encountered.

ESTIMATES OF PERTINENT SPUTTERING YIELDS

In this area, very little information applicable to the space environment has been published, and it will be necessary to estimate the yields without the benefit of theory or adequate experimentation.

The vehicle's environment is composed primarily of hydrogen and helium at all energies and oxygen and nitrogen at energies less than 21 ev. Other constituents are in such small relative abundance that their effect is not significant.

Although the yield varies with angle of incidence, its variance is neither regular nor predictable for various energies and various ion-target combinations. Estimates will be made on the basis of information at normal incidence (at which angle yield is always a minimum), and then doubled to account for effect of angle of incidence — the yield used will thus be high for normal incidence and low for some other angles.

For low energy sputtering by oxygen and nitrogen, a yield curve of the form $S = b(E - E_t)^2$ from threshold to right knee will be used (assuming the point of inflection to be just below the knee). This behavior is predicted by two of the proposed mechanisms and fits the data of Baden, et al. [15] reasonably well for the first few points. The heat of sublimation of an atom, of course, depends on the temperature, crystal, and location of the atom in the crystal; an average value of $E_{sublim} = 4$ ev will be used. Determining the threshold by assuming it to be the heat of sublimation divided by the energy transfer factor, the mean b for $N_2^+ \rightarrow Cu$, $N_2^+ \rightarrow Ni$, $N^+ \rightarrow Cu$, and $N^+ \rightarrow Ni$ from the curves of Baden is roughly 10^{-4}. Assuming $S = 10^{-4}(E-E_t)^2$ for all ion-target combinations at normal incidence, the sputtering yields (doubled to account for angle of incidence) will be as follows for aluminum and silver by oxygen and nitrogen at the energies with which the particles will impinge on the vehicle (Table I):

TABLE I

	E (ev)	$E_{t_{Al}}$ (ev)	S_{Al}	$E_{t_{Ag}}$ (ev)	S_{Ag}
O_2	10.6	4.0	8.6×10^{-3}	5.7	4.9×10^{-3}
	20.8		5.6×10^{-2}		4.6×10^{-2}
N_2	9.3	4.0	5.6×10^{-3}	6.1	2.0×10^{-3}
	18.2		4.0×10^{-2}		2.9×10^{-2}
O	5.3	4.3	2.2×10^{-4}	8.9	0
	10.4		7.5×10^{-3}		4.5×10^{-4}
N	4.6	4.4	8.0×10^{-6}	9.8	0
	9.1		4.3×10^{-3}		0

The thresholds for hydrogen on aluminum and silver are 29 and 110 ev, respectively; those for helium are 8.9 and 29 ev, respectively.

The yields calculated are contingent upon the assumption that low-energy sputtering is a removal phenomenon and that the energy for removal is that of sublimation. If, instead, it is a displacement phenomenon, and if the energy of displacement used in radiation damage theory is correct (~25 ev), no sputtering should occur by particles at the energies under discussion. The possibility that both phenomena are used is discussed in one of the proposals; the consequent threshold lies somewhere between those predicted by the two mechanisms.

From previous discussion and from Fig. 1, it is seen that sputtering by hydrogen and helium depends upon the nature of the target. Extrapolation of the sputtering of H^+ and He^+ on silver in the range 2 to 12 kev, measured by Grønlund and Moore [2] will be used for estimating the sputtering yield for silver; it will be adjusted by the energy transfer factor for other materials.

Grønlund and Moore's data will be used because it is the best available over an extended range. Since it is taken at normal incidence, the figures are doubled to account for the varying yields at different angles.

It will be shown later than no sputtering occurs by atmospheric hydrogen and helium. For other fluxes, the sputtering by particles of energy less than 500 to 1000 ev is an insignificant portion of the total sputtering rate. Sputtering at energies less than those reported by Grønlund and Moore will be obtained by curve-fit extrapolation of their curves down to 1000 ev.

Estimating the sputtering yield at energies greater than 12 kev is difficult due to the necessity of extrapolating over large ranges. Radiation damage falls off approximately as $(\ln E)/E$; if sputtering is an associated phenomenon, it would be expected to decrease in a similar manner. If it is due to an entirely different phenomenon, it may fall off more rapidly, although this is felt unlikely, as it would indicate very negligible sputtering at energies as low as 1 Mev.

It is more likely that sputtering diminishes at a rate less than $(\ln E)/E$. It should reduce, due to the absorption of energy by new phenomena, such as interaction with the electron clouds, etc. There is no reason to expect the yield to rise again with energy.

The yield is assumed to lie between the limits $S(E \geq 12 \text{ kev}) =$ constant and $S(E \geq 12 \text{ kev}) = K(\ln E)/E$, where K is chosen to fit the known value at 12 kev and E is in electron volts. The results are shown in Fig. 3.

SPUTTERING RATES FROM ATMOSPHERE

The composition of the earth's atmosphere at four altitudes is shown in Table II. The primary reference is shown in the right column. The largest contributor to the remaining particles is indicated within parentheses in the proper column.

TABLE II

Height (km)	Temp. (°K)	O_2 (cm^{-3})	N_2 (cm^{-3})	O (cm^{-3})	N (cm^{-3})	Other (cm^{-3})	Ref.
100	199	6.3×10^{11}	6.1×10^{12}	2.1×10^{12}	10^{4}	10^{8} (He)	21
220	1408	10^{8}	4.4×10^{9}	3.4×10^{9}	10^{6}	10^{5} (He)	21
700	1812	0	0	1.1×10^{7}	5.2×10^{7}	10^{3} (He)	21, 22
2500	2500	0	0	1.6×10^{3}	2.3×10^{4}	8.8×10^{2} (H)	22

The energies and velocities of the particles due to thermal motion are negligible compared to those required for sputtering. The mean thermal energy of a particle at 2500° K is only .321 ev and the abundance of particles with E>4 ev is completely negligible. Consequently, the effect of the atmosphere is due entirely to the vehicle's motion through it, and little accuracy will be lost by assuming a stationary atmosphere.

The energy with which a particle strikes the vehicle is given by the square of the velocity of the vehicle times half the mass of the particle ($\pm \frac{3}{2}$ KT - neglected). In this way, we arrive at the energies

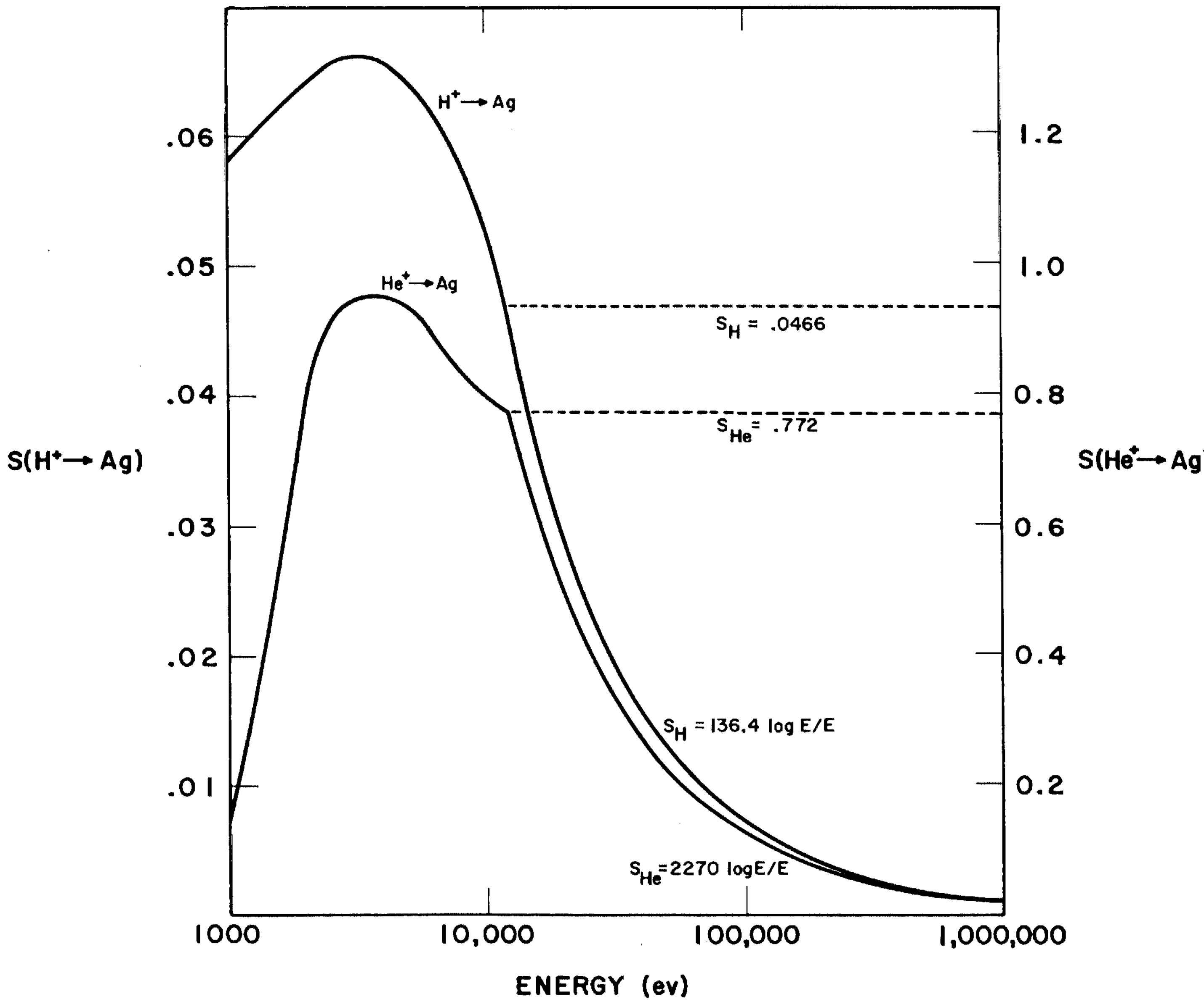

FIGURE 3. ESTIMATED YIELDS OF H^+ AND He^+

of the various particles shown in Table I. The lower energy corresponds to orbital velocity and the higher value to escape velocity.

The associated energies for hydrogen are .33 and .65 ev, for helium 1.33 and 2.60 ev, and for He_2 2.66 and 5.20 ev. These are far below the predicted thresholds and no sputtering occurs due to these particles.

Table III gives the estimated sputtering rate and time to remove 1 Å of aluminum for orbital and escape vehicles, based upon yields given in Table I and the fluxes arising from the motion of the vehicle through the densities given in Table II. Table IV gives the same information for silver.

TABLE III
(Aluminum)

Height (km)	Rate-orbit ($cm^{-2} sec^{-1}$)	Time-orbit (sec/Å)	Rate-escape ($cm^{-2} sec^{-1}$)	Time-escape (sec/Å)
100	3.1×10^{16}	1.9×10^{-2}	3.4×10^{17}	1.8×10^{-3}
220	2.0×10^{13}	30	2.0×10^{17}	3×10^{-3}
700	2.2×10^{9}	2.7×10^{5}	3.4×10^{11}	1.8×10^{3}
2500	4.3×10^{5}	1.4×10^{9}	1.6×10^{8}	3.8×10^{6}

TABLE IV
(Silver)

Height	Rate-orbit	Time-orbit	Rate-escape	Time-escape
100	1.2×10^{16}	4.8×10^{-2}	2.3×10^{17}	2.5×10^{-3}
220	7.0×10^{12}	82	1.4×10^{17}	4.1×10^{-3}
700	----	∞	5.4×10^{9}	1.0×10^{4}
2500	----	∞	8.1×10^{5}	7.0×10^{8}

From these estimates, it is seen that sputtering of vehicles at low altitudes is a serious problem. If the protective shroud were removed at 220 km from an escape vehicle having a 200 Å coating, the coating would disappear in about one second. For a vehicle orbiting at 220 km, it would take about 1.6 hours to remove an aluminum skin 200 Å thick and about 4.6 hours to remove a silver skin of the same thickness. The thermal properties of a quarter wavelength "heat trap" coating would be changed in a short time also. Even if these figures were too high by two orders of magnitude, the sputtering would still represent a serious problem.

Wehner, Laegreid, and Stuart [22] report yields two orders of magnitude below those estimated here and conclude (perhaps incorrectly) that such yields do not represent a serious problem. It is felt that the indirect measurement of yield used by these investigators tends to lower the yield at values much below those measured by weighing. The true yield probably lies between the estimates provided herein and those of Wehner, et al.

The sputtering rates at 100 km are shown to indicate the possible damage to thin coatings caused by early removal of protective shrouds.

The sputtering damage on aluminum at 700 km is of the order of that caused by micrometeorites which should remove 1 Å in about 6 hours [32]. The sputtering rate by the atmosphere at 700 km demonstrates the varied effects on different surfaces; the damage of aluminum is severe enough to remove 1 Å of material in about 7 hours, while silver is not damaged at all. Sputtering by the atmosphere at higher altitudes is not serious.

SPUTTERING RATES FROM SOLAR CORPUSCULAR RADIATION

The flux and energy distribution of the solar corpuscular radiation is not well known and varies widely with solar activity. Considering cometary sputtering and the acceleration of comet tails, Whipple's calculations (revised by Reiffel [23]) show densities of about $600/cm^3$ to $1500/cm^3$ with velocities of 300 to 500 km/sec. Biermann [24] obtains about $100/cm^3$ moving with a velocity of 500 km/sec. At solar maxima, densities as high as $10^5/cm^3$ and velocities on the order of 1500 km/sec are likely [25]; the severe conditions can last as long as 10^3 to 10^4 sec.

It is not known whether or not the energy distribution of the radiation is Maxwellian. The simplifying assumption of a monoenergetic beam will be made. The error caused by this assumption will be less than the error in the figures due to other causes, since neither the flux nor the energies of the particles are well known.

At present, it is generally accepted that the particles originate on the sun's surface; if this is so, and if the same constituents exist in the beam with the same relative abundance as they do on the sun's surface, about one particle in seven will be heavier than hydrogen. Most of these particles will be helium, and for convenience, all of the particles heavier than hydrogen will be assumed to be helium. Assume further that all of the particles are ionized atoms.

For a quiet sun, we shall assume Parker's somewhat conservative figures of a total density of $100/cm^3$ and a proton velocity of 500 km/sec [26]. For an active sun, his figures of a total density of $10^4/cm^3$ and prototype velocity of 1500 km/sec with a storm length of 10^4 sec will be used. From these, the following results are obtained:

Quiet Sun

Particle	Flux ($cm^{-2}sec^{-1}$)	Energy (kev)	Sputtering Rate ($cm^{-2}sec^{-1}$)	& Time (sec/Å)
H	4.3×10^9	1.3	2.6×10^8	1×10^6
He	5.1×10^8	1.3	3.4×10^8	

Active Sun

Particle	Flux ($cm^{-2}sec^{-1}$)	Energy (kev)	Sputtering Rate ($cm^{-2}sec^{-1}$)	& Time (sec/Å)
H	1.3×10^{12}		6.2×10^{10}	3.4×10^3
He	1.5×10^{11}	11.7	1.2×10^{11}	

The solar flare would remove about 3 Å of silver. Bergstralh, et al. [27] and Reiffel [25] obtain figures which agree quite well.

The quiet sun would remove around 30 Å of silver per year. The number of flares per year producing the enhanced flux is not known.

If the larger flux is observed only with solar flares producing polar cap absorption (PCA), which occurs about ten times a year, the active sun would also remove around 30 Å of silver a year.

It is more likely that solar activities producing the enhanced flux of corpuscular radiation occur more frequently and do not require as high solar excursion as do PCA events, which generate high fluxes of high energy ($\gtrsim$10 Mev) protons.

Parker [33] suggests that the quiet and active sun for corpuscular radiation correspond to the quiet and active sun in the sunspot cycle. This, of course, conflicts with Biermann's observations of intense fluxes lasting for 10^4 to 10^5 sec. If Parker is correct, at periods of sunspot maximum, 9.4×10^3 Å of silver would be removed in a year.

One may conclude only that sputtering by corpuscular radiation will remove between 60 and 9.4×10^3 Å of silver per year. Since micrometeorites are thought to erode 10^2 to 10^3 Å per year [32], sputtering removes within an order of magnitude as much material as micrometeorite erosion.

If the yields varied as the energy transfer factor, between 10^2 and 1.5×10^4 Å of copper and 2.5×10^2 and 3.9×10^4 Å of aluminum would be removed in a year by sputtering by solar corpuscular radiation.

Three assumptions have been made which may lower the estimated sputtering rate from the actual value:

(1) It is assumed that associated electrons will not cause sputtering. (This is reasonable, as the associated electrons will have energies less than 200 Kev, the approximate threshold for electrons, if one exists.)

(2) It has been assumed that the number of neutral particles can be neglected. (This is valid if the relative abundance is less than 10^{-2}. The apparent upper limit on the ratio of the sputtering yield of neutral to ionized hydrogen is $\sim 10^2$, and a relative abundance of 10^{-2} would cause the neutral particles to contribute as much to the

sputtering rate as the ionized particles.)

(3) It has been assumed that the relative abundance of particles heavier than helium to the particles of helium is less than 10^{-1}. (The same consequences would hold here, as above, if this were not true.)

It must be emphasized that the density and velocity distribution for important constituents must be known for both quiet and active sun before reliable figures can be obtained. The above figures show that sputtering damage is within an order of magnitude of micrometeorite erosion, which should remove about 100 Å to 1000 Å of metal surface a year.

SPUTTERING RATES BY COSMIC RADIATION, TRAPPED RADIATION BELTS, AND NEUTRON ALBEDO

Neither the total flux nor the differential energy spectrum of the constituents of the trapped radiation belts is known.

Freden and White have measured the differential spectrum from 75 Mev up and find it to fit a curve $N(E) = De^{-E/E_o} dE$, where $E_o = 120$ Mev $\pm$ 5 Mev [28]. From 75 Mev down to .1 Mev, Hess has calculated the differential spectrum by assuming it to originate from the decay of albedo neutrons [29]. If one fits Hess' data and normalizes the curve produced by using Hess' and Freden and White's figures to $N(E>40$ Mev$) = 2 \times 10^4/cm^2$ sec (Van Allen's measurement on Pioneer IV), one obtains a total proton flux of $\sim 6 \times 10^4/cm^2$ sec with energies greater than 0.1 Mev. Assuming the low energy fit can be extrapolated to 0.01 Mev, the added flux is less than 5% and can be neglected. Based on these figures, the sputtering rate by protons on silver in the inner belt is between $80/cm^2$ sec and $2.3 \times 10^3/cm^2$ sec. Although preliminary information from the NERV shots indicates a larger flux at low energies than expected [30] , no significant sputtering could be expected even by greatly revised figures.

Since the density of protons in the outer belt is less than in the inner belt, no significant proton sputtering is expected. Although sputtering by high-energy electrons (>200 Kev) may occur, it is not a serious problem. If electrons had a yield of 10^{-8} at all energies in excess of 200 Kev (a higher yield than should be expected), the peak rate of sputtering would be less than $10^6/cm^2$ sec in the middle of the outer belt, and even less at other points.

By the same argument of low fluxes and low yields, the sputtering rates by galactic and high-energy solar cosmic rays can be neglected. Integral spectra for these particles for selected regions and selected times are shown in [30] .

Hess, Patterson, and Wallace [31] have published a neutron albedo (neutrons created in atmosphere) spectrum which gives a total neutron albedo flux of the order of $10^2/cm^2$ sec. If one assumes the yield of ~ 2 estimated by Moore, et. al. [17] for neutral hydrogen to be equal to that for neutrons (since they are neutral particles of about the same mass), one obtains a sputtering rate of $2 \times 10^2/cm^2$ sec. It is interesting to note that this is as high as that produced by trapped protons, although the protons have a much higher flux.

CONCLUSIONS AND RECOMMENDATIONS

Atmospheric sputtering of low altitude ($\lesssim$350 km) vehicles tentatively appears to be a serious problem. To what degree depends upon the energy at which sputtering begins and the yields near the threshold, an energy region in which little work has been done. The sputtering will remove thin films and destroy the properties of quarter-wave heat trap coatings in a short time.

Wehner, et al. [22] have carried on investigations in this region using an indirect method of determing yield and using a plasma source. An adequate criticism of the plasma source is contained on pp. 4-6 of [22] . However, an investigation of the reliability of their yield measurement at low energies should be made. Although the ion source as used by Baden, et al. [15] has certain advantages, energy resolution and methods of measuring low yields do represent problems.

Investigation of oxygen and nitrogen yields on various surface materials near the threshold should be made to verify the seriousness of atmospheric sputtering indicated in this discussion. In view of the difficulty of fine energy resolution with an ion source, no recommendation of the experimental technique is made, although other factors favor the ion beam.

The only significant sputtering of a high altitude vehicle is accomplished by low-energy (on the order of kevs) solar corpuscular radiation. This mechanism removes within an order of magnitude as much material as micrometeorites at 1 AU and increases as the vehicle approaches the sun. A determination of the fluxes and energy distribution of the radiation constituents will be needed before reliable analysis can be made. Such determination is much more exigent than further experimentation to find yield values for various ion - target combinations in the energy range encountered. Other constituents of the vehicle's environment do not produce sputtering damage.

APPENDIX

1. Present Experimental Techniques

a. Plasma Beam Equipment

The equipment of Wehner, Laegreid, and Stuart [22] represents the greatest refinement of this method.

The experimental tube is a demountable thermionic cathode discharge tube about 40 cm long and 5.7 cm in diameter. The part connected permanently to the vacuum system contains the cathode; the demountable part contains the anode and the target.

The cathode is a standard commercial thyratron cathode. Its activity is maintained by flushing the tube with dry helium and keeping it at $\sim$175 C during the run.

The background pressure does not exceed 8 x 10^{-7} mm Hg. The gases are supplied to the discharge tube by a controlled-leak valve; operating pressures are on the order of 10 microns. The discharge voltage drop is less than 100 volts. The ion current densities range over 3 to 15 ma/cm^2 by varying the discharge current.

The polycrystalline spherical targets are immersed in the plasma-like probes. The ion energy is determined by the negative voltage drop between target and anode, correcting for the potential difference between the plasma near the target and the anode, which is measured by a probe.

The weight loss is measured directly for large yields. For small yields, one takes advantage of the fact that the sputtered atoms find favorable excitation conditions (spiraling electrons) in the plasma.

The emission spectrum of the target is measured by a photomultiplier after the light passes through a monochromator. The curve of the spectral line intensity as a function of bombarding ion energy is fitted to the values of the yields at points which were obtained by weighing.

The yields have not been corrected for secondary emission of electrons due to ion bombardment and may be in error by as much as 30%.

With some materials, it is necessary to sputter large amounts during each run to make negligible the influence of the oxide layer.

The primary disadvantages of a plasma beam are that the angle of incidence cannot be controlled as easily as in an ion beam, that the secondary electron emission cannot be measured simultaneously and that one ionic species cannot be singled out for experimentation.

b. Ion Beam Equipment

The equipment of Baden, Witteborn, and Snouse [15] and their experimental techniques represent a high degree of refinement of ion beam equipment.

The ions are extracted by an r.f. source and are formed by inductive coupling of a 25 megacycle electric field with a low pressure gas contained in a jug. The jug is insulated from the rest of the system and maintained at 3600 V (d.c.). The ions are extracted through a small glass-shielded hole in the jug mounting. Ions are extracted from the plasma sheath surrounding the hole under the influence of the potential drop to a second aperture which is grounded. An axial magnetic field between the apertures varies the ion density at the sheath. The plasma is then at a uniform d.c. potential. The aperture extraction method reduces the total energy dispersion to a minimum; Baden reported energy dispersions of 10 to 100 ev, depending on the r.f. power level.

The extracted beam is focused by an electrostatic lens system, separated by a 90° mass spectrometer, and refocused by a second electrostatic lens system. Separate variable $\pm$ 5 Kev power supplies control each focusing electrode. The lens and suppressor electrodes are current-monitored to eliminate the beam striking them; thus, proper secondary electron suppression is obtained at the target. The secondary electron suppressor consists of a wire grid to minimize reflection of sputtered atoms.

The source pressure is on the order of 10^{-3} mm, and the operaring pressure is below 10^{-5} mm.

The current density is between 10^{2} and 10^{3} μamps/cm^2. The total charge delivered to the target was measured to $\pm$ 1% on a current integrator.

The targets are weighed on a microbalance, accurate to $\pm$ 5 μg, and then inserted in a desiccator to ensure reproducibility of adsorptions. After the run is made, they are returned to the desiccator and weighed. Before each weighing, they are cleaned with solvents such as acetone.

Total weight loss is on the order of 10^{3} μg, with total currents on the order of a coulomb. The energy dispersion in the ion beam is kept below 40 ev. Sputtering yields are taken at both 10^{-5} and 10^{-6} mm Hg.

The angle of incidence measurements are taken, and the surface is repolished when enough sputtering has occurred to introduce an uncertainty in the macroscopic angle of incidence. The greatest problem is measuring yields at low energies because of the large energy dispersion.

2. Survey of Experiments

Early experiments will not be presented, since more recent experiments, run under better controlled conditions, have generally proved the early results to be invalid.

Important investigations are summarized in Table A. 1. Others could be quoted, but the results are not significantly different from these.

TABLE A.1

SURVEY OF RECENT EXPERIMENTS

ION	TARGET	ENERGY	INVESTIGATOR	APPARATUS	REMARKS
H^+, H_2^+, D^+	Ag	925 ev	Moore, Lindner, O'Briain [18]	ion beam, 30 μ amps, ? mm Hg	S measured by radioactive tracers S as a function of angle of incidence
H^o, He^o	Ag	925 ev	Moore, Heldt, Weiss [17]	plasma with ions removed ? mm Hg	S based upon 1 impinging atom per secondary electron observed
H	Cu	15-55 Kev	Pleshivtsev [15]	ion gun 10 μamps 10^{-5} mm Hg	Unanalyzed beam with significant contaminants - extraordinarily high S
H^+, H_2^+, D^+	Ag	2-12 Kev	Grønlund and Moore [2]	ion beam 100μamp 10^{-6} mm Hg	
Ar^+, He^+, D^+	Cu	5-40 Kev	Yonts, Normand, Harrison [12]	ion beam 78 μamps 10^{-4} mm Hg	Also preliminary data on Cu at 30 Kev by H^+, D^+, He^+, N^+, Ar^+, Cu^+, Kr^+, U^+ and by A^+ on Ta, Mo, Al
Ar, H	Cu	5-50 Kev	Yurasova <u>JETP 37</u>, 689	ion beam	Study of directed emission off a copper monocrystal
N^+, N_2^+	Cu, N, Fe, Mo, W	0-8 Kev	Bader, et. al. [16]	ion beam 100 μamps 10^{-5} mm Hg	Study at normal and 45^o incidence; thorough analysis of results
H, N, Ne, Hg, He	38 metals	20-1000 ev	Wehner, et. al. [23]	plasma beam 10 ma 10^{-3} mm Hg	Thorough report and commentary
Hg	Ni, Pt, Ge, Mo	100-1000	Wehner and Rosenberg [1]	plasma beam 5 ma 10^{-3} mm Hg	Angular distribution of sputtered material
Hg	Fe, Ta, Mo, A, Ag, Pt	125-800 ev	Wehner [14]	plasma beam 1.2 μamps 10^{-3} mm Hg	Influence of angle of incidence on sputtering yield

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